Superconductor Science and Technology

Influence of magnetic fields on hysteretic ac losses in bulk MgB_2 superconductor investigated by using Hall probe ac susceptibility method

To cite this article: A Varilci 2007 *Supercond. Sci. Technol.* **20** 397

IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **20** (2007) 397–400 doi:10.1088/0953-2048/20/4/016

Influence of magnetic fields on hysteretic ac losses in bulk MgB_2 superconductor investigated by using Hall probe ac susceptibility method

A Varilci

Faculty of Arts and Sciences, Department of Physics, Abant Izzet Baysal University,
14280 Bolu, Turkey

E-mail: varilci_a@ibu.edu.tr

Received 10 January 2007, in final form 20 February 2007
Published 7 March 2007
Online at stacks.iop.org/SUST/20/397

Abstract

We report the results of an investigation of the influence of magnetic fields on hysteretic ac losses in bulk MgB_2 superconductor by using Hall probe ac susceptibility. The external magnetic field in this study had an ac part with frequency 10 Hz and magnitude in the range 240–1200 A m^{-1} and no dc part. We have measured the imaginary part of the magnetic susceptibility and analysed data by using Bean's critical state model of cylindrical geometry for four different temperature values 39.55, 39.51, 39.47 and 39.41 K. The result of this analysis indicates that Bean's model is adequate to explain the experimental findings. Calculated hysteretic ac loss versus applied magnetic field curve is given by using the critical state model. We have also measured the magnetization versus applied magnetic field and determined the first critical magnetic field of a MgB_2 sample as 500 A m^{-1} at 35 K.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The ac susceptibility method provides useful information on bulk magnetic susceptibility which has a real (χ') and imaginary part (χ''). Under an external magnetic field, the imaginary part of susceptibility for the type II superconductors can show two peaks, if the external field is above a critical value. This phenomenon is believed to be due to inter-grain and intra-grain related effects. By using this fact, one can calculate the inter- and intra-grain critical current density [1].

The discovery of MgB_2 [2] as a non-ceramic type II superconductor with a relatively high critical current density ($J_c < 1$ MA cm^{-2}) compared to those of YBCO [3] and BSCCO [4] created a lot of interest in this material. One of the most crucial parameters of type II superconductors is the critical current density which tends to decrease with increasing ac losses due to vortex motion. So, the detailed study of ac loss has paramount importance for the possible commercialization of superconductors. The ac susceptibility measurement technique provides complete information on the ac hysteretic loss. It is obvious that any experimental and theoretical study to analyse the parameters affecting ac loss will make an important contribution to the literature. Muller [5] comprehensively studied the ac loss theoretically and experimentally. The ac loss, W, which is the area under the magnetization versus applied field curve, is related to the imaginary part of the ac susceptibility by the following simple expression:

$$\chi_1'' = W/\mu_0\pi H_{ac}^2 \qquad (1)$$

where H_{ac} is the applied field and the subscript 1 refers to the fundamental susceptibility.

The Hall probe ac susceptibility (diamagnetic shielding) method was used (for details see Senapati [6], Zhukov [7] and Stamopoulos [8]) to investigate the inter-grain and intra-grain properties of superconductors, especially for small crystalline HTS samples. The study of pinning properties as well as the vortex dynamics by miniature Hall probe susceptibility can give local information about the hysteretic ac loss. In

0953-2048/07/040397+04$30.00

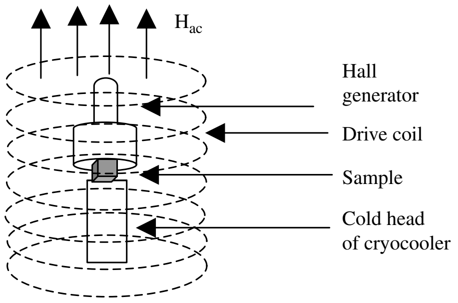

Figure 1. Sketch of Hall probe ac susceptibility set-up. Drive coil that generates the ac field has 720 turns. The sample is placed at the centre of this coil.

this work, we carried out detailed Hall probe ac susceptibility measurements and its applicability to investigate the harmonics of susceptibility of the MgB_2 superconductor. Measurements were interpreted by Bean's critical state model for cylindrical geometry [9]. In section 2, we give the details of the experiment. The results are reported and discussed in section 2.

2. Experimental details

A commercial powder of MgB_2 from Alfa Aesar Company was used to make a pellet. The pellet was prepared by pressing the powder to get a disc sample of 10 mm diameter under 750 MPa pressure at room temperature. The pellet with thickness 3 mm was wrapped with Ta foil then placed in a quartz tube for heat treatment. The annealing temperature was selected as 850 °C for 1 h in flowing Ar gas. After annealing, the sample was stuck on the copper cold head of the cryocooler by GE varnish. Then, the Hall generator with 0.55 mV kG^{-1} magnetic sensitivity and 0.08 cm diameter active area was placed on the sample. A 200 mA control current was applied to the Hall generator. A Si diode, fixed on the cold head, was used to read the temperature of the sample. The uncertainty of temperature measurements is about 1 mK. The measurements were started at a heating rate of 0.5 K min^{-1} in the temperature range 30–45 K at ac field amplitudes of 240, 480, 720, 960 and 1200 A m^{-1} at 10 Hz frequency. A Lake Shore 332S-T1 temperature controller was used for temperature sweeping. Susceptibility data, taken from the lock-in amplifier, were recorded using a LabView computer program. Since the signal generated from the Hall probe was very weak, a Tegam model 73 precision ratio transformer was used for a voltage amplifier. Figure 1 shows the measuring part of the Hall probe ac susceptibility system. The ac field sensed by the Hall generator depends on the strength of the shielding ability of the sample when the sample is in a superconducting state. If H_0, produced by the coil, is the field strength of the ac field, field strength on the thin sample detected by the Hall probe is described by $H_c = H_0 \cosh(\frac{a_0}{\lambda_{ac}})$, where λ_{ac} is the penetrating depth and a_0 is the circumference of the thin bulk sample [6].

In the limit of strong flux pinning, the response is highly nonlinear in ac field strength, and Bean's critical state model [9] can be used to calculate the critical current density. In the limit of $H_{ac} \ll J_c d/2$, where d is the sample thickness, the components of fundamental susceptibility (χ' and χ'') are given by the relations

$$\chi' = -\chi_0[1 - \tfrac{15}{32}x^2] \tag{2}$$

and

$$\chi'' = \chi_0 \frac{x^2}{\pi} \tag{3}$$

where $x = 2H_{ac}/J_c d$ and $\chi_0 = 8a_0/3\pi d$. Numerical solutions of Clem and Sanchez [10] show that the peak in χ'' occurs at $x = 1.942$, which implies $H_m = 0.97 J_c d$, where H_m is the ac field amplitude corresponding to the peak in χ''. Since $\chi'' = T''_H$ (T''_H is the imaginary part of transmittivity), a measurement of T''_H as a function of ac field amplitude directly gives the J_c.

3. Results and discussion

We display the real and imaginary parts of ac susceptibility measured as a function of temperature at five different applied fields in figures 2(a) and (b), respectively. As seen in figure 2(a), the inter-granular peak of the imaginary part of susceptibility shifts to lower temperatures and broadens as the ac field increases from 240 to 1200 A m^{-1}. The amount of the shift as a function of ac field amplitude is proportional to the strength of the pinning force [11]. The peak temperature (T_p) values found from this figure are 39.60, 39.50, 39.40, 39.35 and 39.30 K for 240, 480, 720, 960 and 1200 A m^{-1}

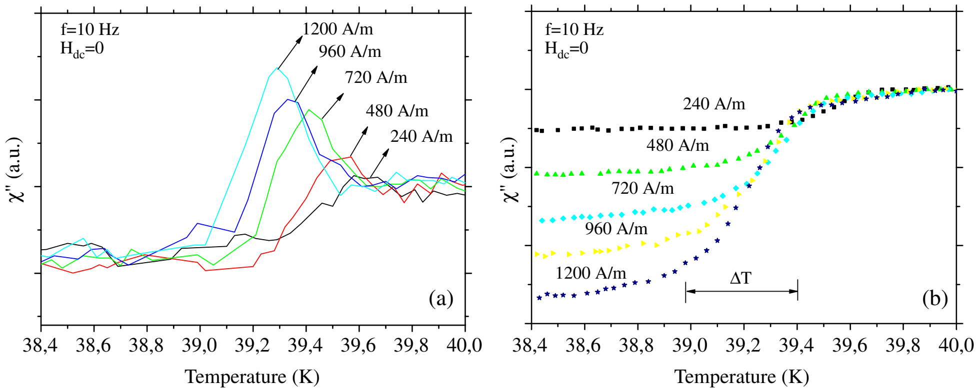

Figure 2. Hall probe ac susceptibility of (a) imaginary part and (b) real part versus temperature plots for MgB_2 sample annealed at 850 °C.

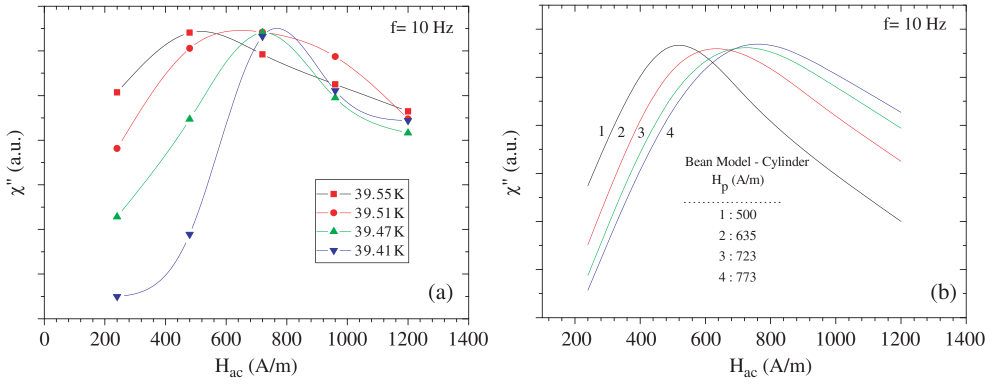

Figure 3. (a) The graph of the imaginary part of the ac Hall probe susceptibility versus the applied field extracted from figure 2(a) at different temperatures. (b) The calculated χ'' (H_{ac}) data, which is plotted by using Bean's critical state model.

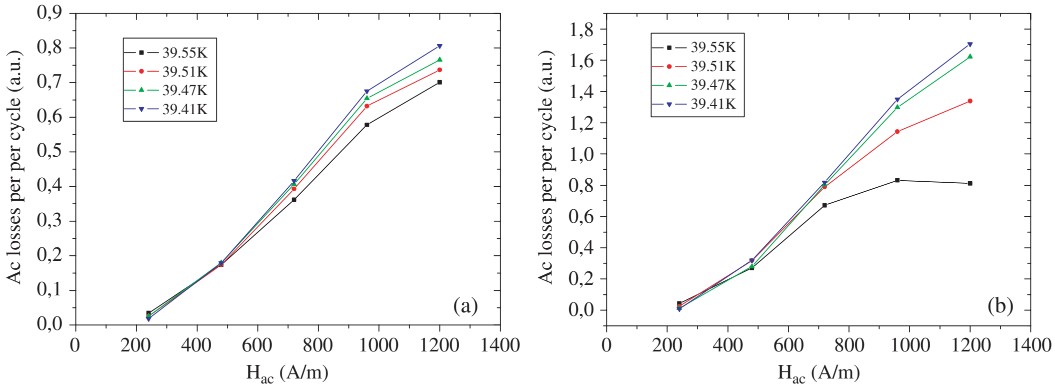

Figure 4. The plot of (a) experimental and (b) theoretical ac losses versus applied magnetic field (the same temperatures are given in figures 3(a) and (b)).

applied fields, respectively. No intra-grain peak arising from the irreversible motion of Abrikosov-like vortices inside the grains was observed. The width of the inter-granular loss peak is about 0.4 K at H_{ac} equal to 1200 A m^{-1}. This temperature gradient is nearly equal to the transition width as denoted by ΔT in figure 2(b). The real part of the susceptibility shows a single step behaviour at transition to the full superconducting state as can be seen from figure 2(b). The Hall probe voltage (V_{Hall}) at $H_{ac} = 240$ A m^{-1} displayed in figure 2(a) is very weak because at this value of the external field, the shielding of the field by the MgB$_2$ sample is almost complete. As the external field strength is increased, the shielding gets weaker as is seen from the V_{Hall} value at $H_{ac} = 1200$ A m^{-1} which is about four times the Hall voltage at $H_{ac} = 240$ A m^{-1}.

We extract the imaginary part (χ'') of the ac susceptibility at four different temperatures from figure 2(a) and display the external field-dependent χ'' values as figure 3(a). Figure 3(b) depicts the calculated χ'' values using Bean's critical state model for cylindrical geometry using the penetrating field, H_p. H_{ac} is the applied ac field and the peak of the out-of-phase component (χ'') occurs at $H_{ac} = H_p$ [12]. H_p values were found to be 500, 635, 723 and 773 A m^{-1} for 39.55, 39.51, 39.47 and 39.41 K, respectively. According to Bean's critical state model for cylindrical geometry, the imaginary susceptibility values are given as follows:

$$\chi'' = \left[\left(\frac{4H_{ac}}{H_p}\right) - \left(\frac{2H_{ac}^2}{H_p^2}\right)\right]\frac{1}{3\pi} \qquad H_p \geqslant H_{ac} \qquad (4)$$

$$\chi'' = \left[\left(\frac{4H_p}{H_{ac}}\right) - \left(\frac{2H_p^2}{H_{ac}^2}\right)\right]\frac{1}{3\pi} \qquad H_{ac} \geqslant H_p. \qquad (5)$$

The χ''–H_{ac} relation can be analysed by using Bean's critical state model for cylindrical geometry. One of the key concepts of this model is the penetrating field H_p which is defined as the value of the external field H_{ac} at which the peak of the imaginary part of ac susceptibility occurs.

The ac hysteretic loss, W, is calculated by using equations (1), (4) and (5) along with the data extracted from figure 3(a) and displayed as a function of external field in figure 4(a). The theoretical values for W are obtained from Bean's model and shown in figure 4(b). From a comparison of these two figures, it is reasonable to say that the experimental results and the predictions of Bean's model agree well up until $H_{ac} = 500$ A m^{-1}. After $H_{ac} = 500$ A m^{-1}, the agreement gets worse as the external field is increased, especially at $T = 39.55$ K [13]. This finding is interesting because Bean's critical state model was found to be valid for a large range of external fields for ceramic high temperature superconductors [14].

We have also measured the applied dc magnetic field dependence of the penetrating field by the Hall probe and

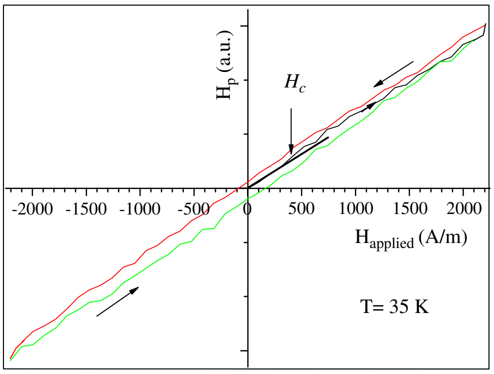

Figure 5. The applied magnetic field, H_{applied}, versus the penetrating field, H_{p}, for the MgB_2 sample at 35 K.

display the findings in figure 5. As can be seen from this figure, H_{p} is linear up to a critical applied field of $H_{\text{c}} = 350$ A m^{-1}. The first critical field H_{c1} can be determined using the following equation [7]:

$$H_{\text{c1}} = \frac{H_{a-c}}{1 - N}. \tag{6}$$

Here, N is the demagnetizing factor along the applied magnetic field direction. For a thin disc, $N_{\parallel} = 1 - (\pi d/2D)$ and $N_{\perp} = \pi d/4D$ can be used for magnetic field direction parallel and perpendicular to the disc axis, respectively. Here, d and D are used as the thickness and diameter of the sample, respectively. H_{c1} is calculated for our sample as 500 A m^{-1} at 35 K.

In summary, we have investigated the fundamental ac susceptibility of MgB_2 using the local Hall probe method. This measurement method allowed us to study local regions (a disc of 0.08 cm diameter) of the sample. The real and imaginary parts of susceptibility are measured for magnetic fields starting from 240 to 1200 A m^{-1}. Then, the imaginary part of susceptibility versus applied magnetic field is plotted for 39.55, 39.51, 39.47 and 39.41 K. The imaginary part of susceptibility is also plotted against applied field using Bean's critical state model for cylindrical geometry. The ac hysteretic losses are measured by experiment and calculated theoretically. There is an agreement up to 500 A m^{-1} between experimental and theoretical curves. Finally, H_{c1} is determined as 500 A m^{-1} at 35 K by magnetization versus applied dc magnetic field.

Acknowledgments

This work has been financially supported by the Turkish Research and Scientific Council (TUBITAK) under grant contract no. 104T324. We are grateful to Dr Resul Eryigit for many helpful discussions and Mr Dincer Yegen for sample preparation.

References

[1] Feldmann D M *et al* 2001 *Appl. Phys. Lett.* **79** 3998
[2] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y and Akimitsu J 2001 *Nature* **410** 63
[3] Goldfarb R B, Latental M and Thompson C A 1991 *Magnetic Susceptibility of Superconductors and Other Spin Systems* ed R A Hein, T L Francavilla and D H Liebenger (New York: Plenum) p 49
[4] Düzgün İ, Karaca İ, Öztürk A and Çelebi S 2006 *Physica* C **436** 93
[5] Müller K H 1991 *Magnetic Susceptibility of Superconductors and Other Spin Systems* ed R A Hein, T L Francavilla and D H Liebenger (New York: Plenum) p 229
[6] Senapati K, Chakrabarty S, Leena K Sahoo and Budhani R C 2004 *Rev. Sci. Instrum.* **75** 141
[7] Zhukov A A, Bush A A, Gladyshev I V, Gordeev S N and Moshchalkov V V 1990 *Z. Phys.* B **78** 195
[8] Stamopoulos D and Pissas M 2001 *Supercond. Sci. Technol.* **14** 844
[9] Bean C P 1962 *Phys. Rev. Lett.* **8** 250
[10] Clem J R and Sanchez A 1994 *Phys. Rev.* B **50** 9355
[11] Salamati H and Kameli P 2003 *Solid State Commun.* **125** 407
[12] Terzioglu C, Yegen D, Yılmazlar M, Gorur O, Akdogan M and Varilci A 2007 *J. Mater. Sci.* doi:10.1007/s10853-006-0541-6 at press
[13] Gencer A, Aksu E, Yılmaz H and Aydınuraz A 2002 *Supercond. Sci. Technol.* **15** 592
[14] Ozturk A and Celebi S 2006 *J. Alloys Compounds* **421** 4